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Evaluation of cone resistance results from Dutch Formula

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ABSTRACT

The Dynamic Penetration Test (DPT) is widely applied for soil field characterization. The technique is usually appreciated as a simple and cost-effective means of determine soil resistance which can be obtained either from Newtonian or from wave equation methods. While wave equation analysis has demonstrated numerous advantages in recent decades, its adoption is constrained by the need for specific instrumentation and more complex analysis. Consequently, the simpler Newtonian analysis, and particularly the Dutch Formula specified by ISO 22476-2, remains the more commonly used approach for routine geotechnical applications. To ensure its accuracy comparing to wave equation-based methods, a field campaigns were conducted on experimental sites with various soil types. The campaigns included Cone Penetration Test (CPT), which is used as a reference tool in this study, and instrumented DPTs allowing easy application of wave equation methods. Results revealed that Dutch Formula resistance values were comparable to both CPT results and those derived from wave equation methods in most cases. In addition, DF variation formula applying energy measurement seemed to underestimate cone resistance in all case examined. The study highlights the importance of applying good practice rules to enhance DPT results.

Keywords: In situ soil characterisation; Dynamic Penetration Tests; Wave equation methods; Dutch Formula.

1. Introduction

Dynamic penetration test (DPT) is a widely applied technique for soil in situ characterisation. DPT is often appreciated for being a simple, economical, and fast means of soil investigation and of soil resistance assessment. Soil resistance (q_d) can be determined from DPT data using different analysis approaches.

In fact, expressing DPT results in terms of q_d and not as a number of blows per penetration (e.g. N_{10}, N_{20}, N_{30}) is strongly recommended as it allows a more universal way of expressing test results, which enables comparing and combining results from different size penetrometers (DPL, DPM, DPH or DPSH) (Butcher, McElmeel, and Powell 1996; EN ISO-22476-2 2005). To determine q_d from DPT data, two most common approaches are Newtonian analysis (from which driving formulas are derived) and wave analysis-based analysis.

In the last decades, several studies have demonstrated the numerous benefits of applying wave equation analysis to DPT interpretation once it provides better description of dynamic penetration phenomena and the assessment of newer soil parameters from DPT. Nevertheless, these wave equation approaches require specific instrumentation (e.g. accelerometers, strain gages, displacement sensors) and the application of more complex analysis. Thus, practical, and cultural reasons wave equation analysis remain not commonly applied in routine geotechnical applications. Despite representing a significant improvement that wave equation analysis represents in dynamic testing interpretation, it is important to verify if simple Newtonian derived method preconize by current standard ISO 22476-2 (i.e., Dutch Formula) can produce satisfactory resistance results. It is especially important to know if Dutch Formula (DF) is suitable for soil resistance assessment when good practice rules (e.g. energy measurement, skin friction control) are considered.

For that, field campaigns testing different experimental sites with various type of soils were conducted. These campaigns comprised several DPTs and CPT. Instrumented DPTs are applied enabling easy application of wave equation methods as it is described in the following sections. In this study, CPT results are used as reference tool to evaluate cone resistance derived from various methods from DPT data.

1.1 Interpretation methods

Two most approaches commonly applied for DPT data interpretation are Newtonian analysis and wave equation-based analysis. For each one of these approaches, numerous methods were derived (ENR 1965; Gates 1957; Hiley 1925; Janbu 1953). Amongst methods derived from Newtonian approach, this paper focus on DF for its largely acceptance and as this is the method recommended by standard ISO 22476-2 (2005).

DF can be deduced from shock analysis of dynamic penetration phenomenon considering the impact perfectly inelastic, penetrometer and soil elastic deformations negligible as well as the assembly work of inertial force after impact equals zero. Cone resistance according to DF ($q_{d,DF}$) can be calculated using Eq.(1).

$$q_{d,DF} = \frac{1}{A_t}\frac{MgH}{e}\frac{M}{(M+P)} \tag{1}$$

With A_t the cone cross sectional area, M the hammer mass, g the gravitational acceleration (9.81 m/s^2), H the free fall height and e the penetration for each blow and P the penetrometer mass. A more detailed derivation of DF is provided by (Frazer 1971).

Other interpretation approach allow to express results in terms of cone resistance is based on wave equation based. Considering homogenous elastic rod with uniform section, if external forces (e.g. skin friction) along the rods are negligible, propagation of the wave u(x,t) through the rod can be described by the so-called wave equation (Eq.(2)) (Saint-Venant 1867).

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c^2\frac{\partial^2 u(x,t)}{\partial x^2} \tag{2}$$

With c equals the velocity of compressional wave that propagates within the rod. One of the most employed solutions for wave equation is provided by the so-called characteristics method shown in Eq. (3).

$$F(x,t) = f(x-ct) + g(x+ct) \tag{3}$$

Functions *f* and *g* are the superposing of waves travelling downward and upward through the penetrometer rods. Moreover, the energy transmitted to the penetrometer during the hammer blow, and which drives cone penetration into the soil can be calculated from Eq. (4), where F(t) and v(t) are force and velocity measurement performed in penetrometer rods during a impact as stated by the standards ASTM D 4633 (ASTM 2010) and EN ISO-22476-2 (CEN, 2005).

$$EFV = \int F(t)\, v(t) dt \tag{4}$$

Based on wave equation approach, several cone resistance determination methods emerged. Main methods existing which are examined in this study are briefly described as follows.

- Case Method (Case) proposed by (Goble, Rausche, and Likins 1975; Rausche 1970) and originally introduced for driven piles.

$$q_{d,Case} = \frac{1}{A_t}[F_A(t_1) + F_A(t_1 + 2\,L/c)] + \frac{Z_t}{A_t}[v_A(t_1) - v_A(t_1 + 2\,L/c)] \tag{5}$$

With $F_A(t)$ and $v_A(t)$ are force and velocity signals measured at point A in the pile head at the initial time t_1 taken as time for which force $F_A(t)$ is maximum.

- Simplified Method (SM) proposed by (Paikowsky and Chernauskas 1992). As for Case Method, SM was originally proposed as a bearing capacity estimation method for piles. The method is based on EFV and displacement measurements and expressed as in the Eq. (6).

$$q_{d,SM} = \frac{1}{A_t}\left(\frac{EFV}{s_p + \frac{s_e}{2}}\right) \tag{6}$$

With s_p the permanent displacement and s_e the elastic displacement. Elastic displacement s_e being the difference between s_p and the maximum displacement. In this study, the term $s_e/2$ is assumed negligible.

- Unloading Point Method (UPM) proposed by (Middendorp, Bermingham, and Kuiper 1992) for Statnamic pile tests analysis. Based on soil-pile interaction, this method defines the resistance as the total resistance measured at moment when velocity is zero. Unlike pile application, damping forces in the case of test examined in this work are not significant due to penetrometer small mass. Hence, mass contribution is neglected in the case. According to this method, resistance is determined as shown in Eq. (7).

$$q_{d,UPM} = \frac{1}{A_t}\,[K'\,s(t) + M'\,a(t)] \tag{7}$$

With *K'* the spring constant and *M'* the mass. The displacement, and acceleration expressed by s(t), and a(t) respectively.

- Tip Force Integration Method (TFIM) proposed by (Benz Navarrete, Breul, and Gourvès 2022; Tran, Chevalier, and Breul 2016) propose determine soil resistance. The method is based in a specific wave analysis allowing tip signals assessment. Then, soil resistance is derived directly from tip force integration.

$$q_{d,TFIM} = \frac{1}{A_t}\left(\frac{1}{s_{max}}\int_0^{s_{max}} F_t\, ds\right) \tag{8}$$

With F_t the force at penetrometer tip and s_{max} the maximum displacement at penetrometer tip.

In addition to DF and to wave equation methods, other method examined in the work is a variation of DF recommended by EN ISO 22476-2 (2005). The variation consists of replacing potential energy (*MgH*) in the original DF formulation for EFV (Eq. (4)). This alternative application of DF is referred in the present article as DF-EFV (Eq. (9)).

$$q_{d,DF} = \frac{1}{A_t}\frac{EFV}{e}\frac{M}{(M+P)} \tag{9}$$

2. Experimental testing campaign

The field test campaign carried out in three experimental sites in which a series of instrumented DPT and CPT comparative tests were conducted. Tests performed as well as test sites selected are described in the following sections.

2.1 Dynamic and static tests

Multiple DPTs were conducted using two instrumented dynamic penetrometers: an instrumented Dynamic Penetration Lightweight (DPL) and an automatic Dynamic Probing Super Heavy (DPSH) type B (EN ISO-22476-2 2005).

The DPL employed possesses a conical tip of 90° apex angle, 22.5 mm diameter and hence 4 cm^2 cross-sectional area. A stem rod of 1 m length and 14 mm diameter is employed. The ratio between the diameters of the cone and the rod (~ 1.61) allows to minimize skin friction during a test. The instrumentation applied to the penetrometers allows to measure force, velocity and displacement signals close to the anvil during driving. By means of wave separation and reconstruction methods, force, velocity, and displacement signals can be also estimated at the cone tip. A complete description of the equipment and its measurement principle are provided by (Benz Navarrete, Breul, and Gourvès 2022).

Concerning DPSH, its drive energy is 473 J (hammer of 63.5 kg and fall height of 760 mm). Moreover, 1 m long rod with a diameter of 32 mm is used, while a conical tip with an apex angle of 90°, a diameter of 50.5 mm and a cross-sectional area of 20 cm^2 is employed. A more detailed description of the equipment is provided by (Benz-Navarrete, Breul, and Moustan 2019).

Apart from DPT performed, for each site, several CPT results were available. CPTs examined in this study are mechanical CPT data from historical database of National Projects experimental sites and those conducted more recently with electrical cone. In the case of mechanical cone results vertical resolution was of 0.2 m whereas vertical resolution of electrical cone results was of 0.01 m. Resistance profiles obtained with mechanical CPT are indicated CPTM whereas electrical CPT results are simply noted CPT.

2.2 Test sites and field campaign

Three well-documented experimental sites — Jossigny, Cran, and Sète — were chosen for field tests. At Jossigny, located in eastern Paris, the soil primarily consists of silty layers, with a groundwater table between 1 and 2 meters below the surface (Combarieu and Canépa 2001; Grasson et al. 2015; Reiffsteck and Nasreddine 2002).

Cran, situated west of Nantes, France, shows some homogeneity with soft, cohesive sediments from 5 to 10 m depth (Bat, Blivet, and Levacher 2000; Paute 1973; Puech, F., and E. 1982). Sete, an embankment in the port of Sete, shows high vertical and horizontal heterogeneity (Reiffsteck et al. 2020; Teyssier et al. 2020). Selected sites provide diverse geological conditions, allowing for a comprehensive investigation of soil properties through various penetration tests. Location, number of soundings and maximum reached depths (z_{max}) are presented in the Figure 1.

On each site, instrumented DPT were performed as close as possible to the CPT tests. The verticality of the tests was observed, and the skin friction of the rods was evaluated either manually or using a torque wrench every 1 m penetration during tests.

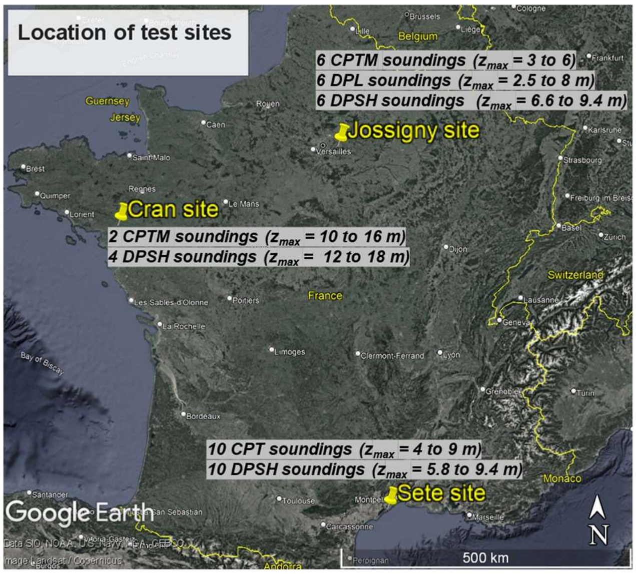
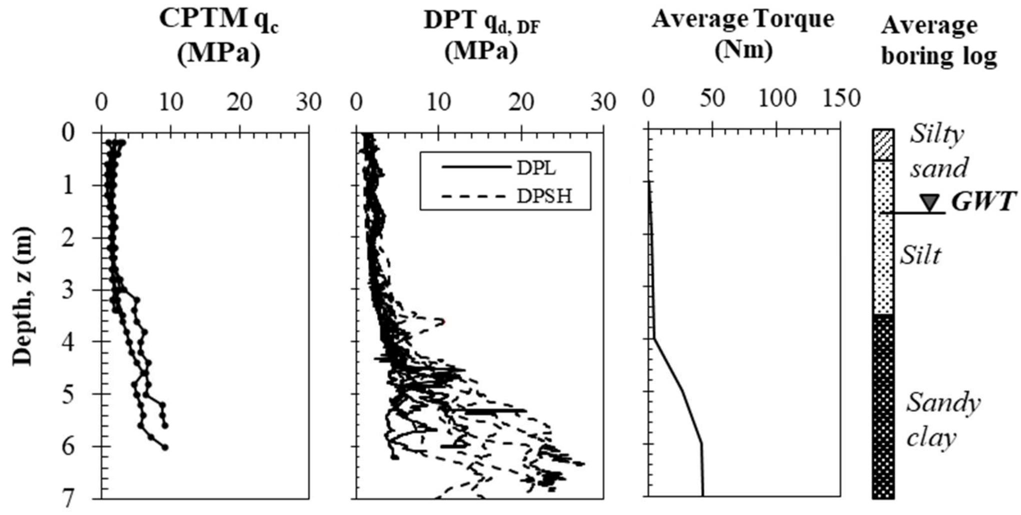


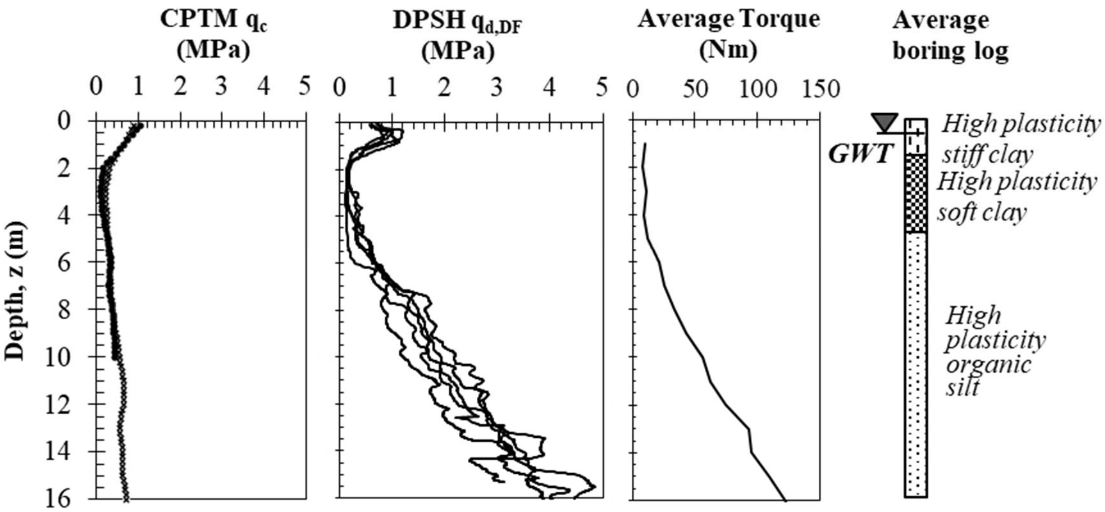
Figure 1. Location, number of soundings and maximum depths (z_{max}) (image ©2024 Google)

For dynamic results presenting significant skin friction (Jossigny and Cran site results), correction method proposed by (Dahlberg and Bergdahl 1974) was employed. This correction is based on torque required to rotate the rod as a means of separating the skin resistance from the cone resistance. Energy necessary to rotate the rod is calculated and subtracted from the energy delivered by the impact. This approach assumes that the average skin friction resistance along the rod is the same when the rod is driven down by the hammer as it is when the rod is rotated, and the torque is measured. A full description of the method is provided in (Dahlberg and Bergdahl 1974).

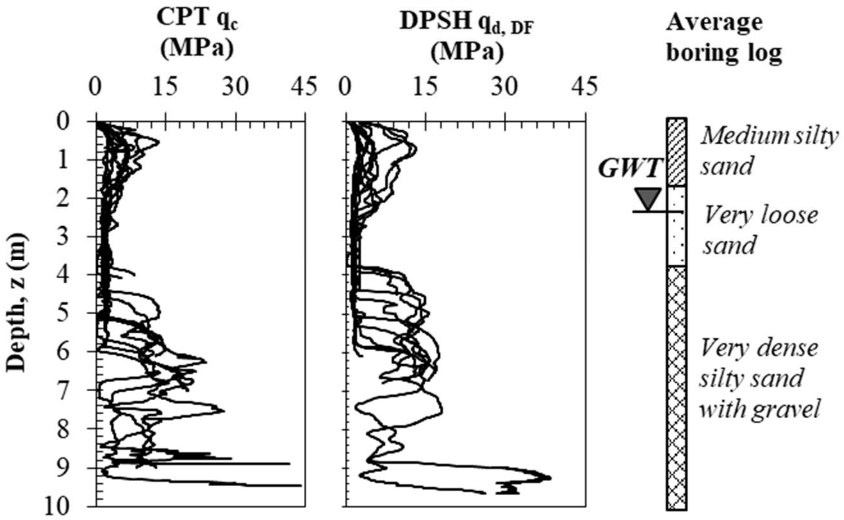
Figure 2 presents the CPT cone resistance (q_c) and dynamic resistance profiles for each site. Dynamic resistance is determined with DF in accordance with (EN ISO 22476-2 2005). In addition to resistance profiles, soil stratigraphy and groundwater table (GWT) are also included in Figure 2. For Jossigny and Cran sites (Figure 2a and b), average torque measurement profiles are also presented. No considerable skin friction was observed during Sete site tests.



(a)



(b)



(c)

Figure 2. Mechanical CPT (CPTM) and electrical CPT (CPT), DPT (DPL and DPSH), and torque measurements profiles and soil boring logs for the sites: (a) Jossigny site, (b) Cran site, and (c) Sète site

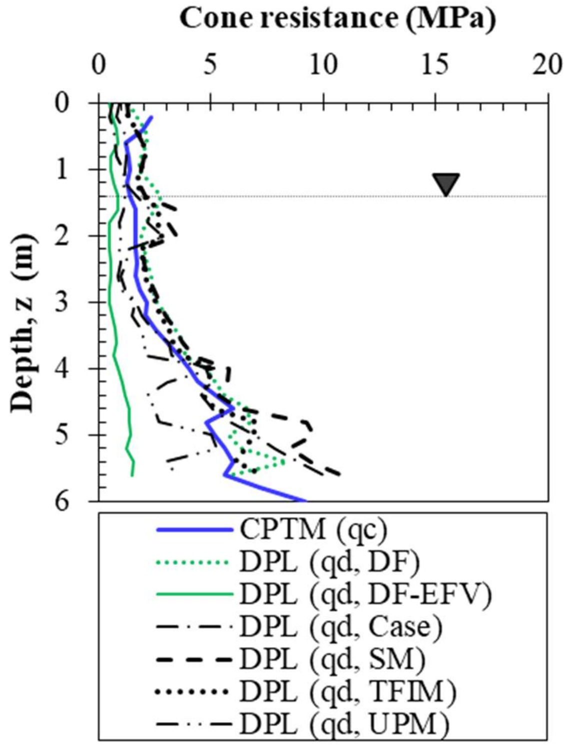
As observed from resistance profiles shown in Figure 2, Cran site exhibits a more homogenous profile than the other sites examined. Jossigny site presents some heterogeneity for deeper zones (approximately superior to 4 m), whereas Sète site is highly heterogeneous, especially for depth superior to approximately 4 m. Sete site heterogeneity can be explained by its construction method as the site is a marine sand dredged embankment. Overall, the sites selected allow to examine various soil types ranging from fine-grained soils to sands.

3. Results and discussion

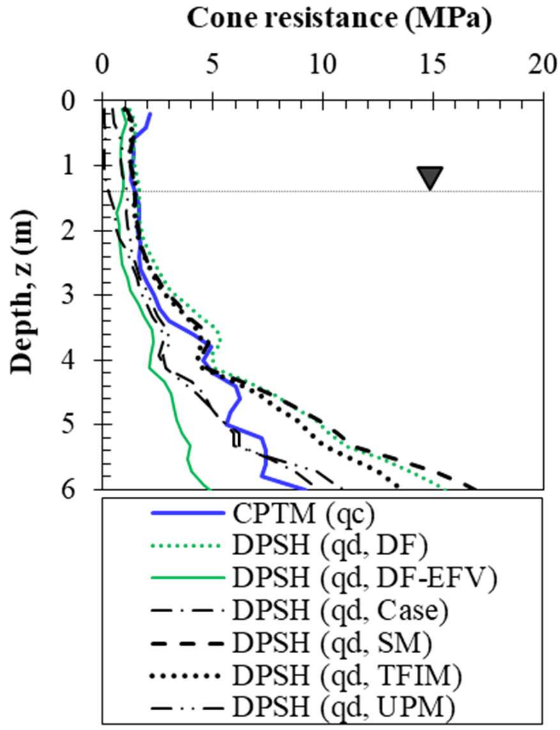
In the section, results from DPT derived from different methods is presented. DPT are then compared to average CPT profiles used as the reference result. Because vertical resolutions of DPT and CPT are not the same, to compare resistance profiles from all techniques, results are regularized. DPTs applied in this study present high vertical resolution provide quasi-continuous soil profiles (each 5 mm). In contrast, CPT vertical resolution varies for tested sites from 0.2 m (mechanical cone results) to 0.01 m (electrical cone results). A regularization step of 0.2 m is applied to all resistance profiles (CPT and DPT) to facilitate comparison between different results.

The Figure 3 presents the average resistance profiles derived from DPT data applying different methods and CPT results for Jossigny site. Figure 3a shows results of DPL and CPT whereas Figure 3b presents results of DPSH and CPT.

Overall, in Figure 3a, the DF and TFIM methods demonstrate a better agreement across the entire profile, while SM and UPM results diverge, particularly at greater depths ($z > 4$ m) where site heterogeneity is more prominent. DF-EFV method produces lower values for the entire profile. In Figure 3b, the DPSH results reveal that, for shallow layers ($z < 4$ m), all methods except Case and DF-EFV show comparable results to q_c, with a variation of approximately ± 30%. Conversely, at greater depths (> 4 m), DF, SM, and TFIM exhibit a progressive increase, surpassing q_c by more than 70% at 6 m. The Case method consistently underestimates q_c until a depth of about 5 m, resulting in an average $q_{d,Case}$ that is 34% lower than q_c across the entire profile. As for DPL results, DF-EFV tend to underestimate resistance as it produces the lowest values beyond 2 m depth.



(a)



(b)

Figure 3. Average resistance profiles for Jossigny site: (a) DPL and CPTM; (b) DPSH and CPTM

To investigate deeper layers, DPSH were used in Cran site tests where profiles reached 16 m depth. The Figure 4 presents the average resistance profiles derived from different methods from DPT data and CPT results for Cran site.

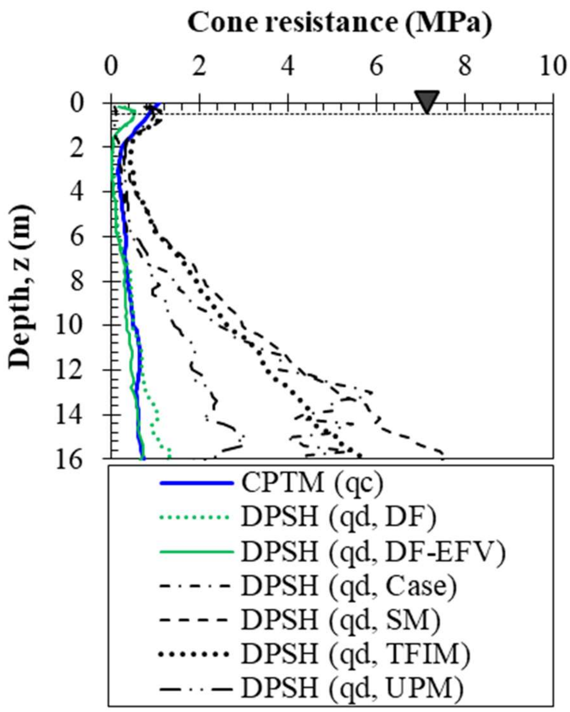


Figure 4. Average resistance profiles for Cran site obtained with DPSH and CPTM

As shown in Figure 4, most methods produce greater resistance than q_c. For shallow depths (inferior to 2 m), Case method results were considerably lower than all other methods and lower than q_c. DF and DF-EFV presented the best correspondence to q_c. Amongst, wave equation-based methods, UPM produced better results which are nevertheless considerably superior to q_c for deeper layers.

The overestimation of resistance by most methods can be attributed to the notably high skin friction observed at this site, as indicated by torque measurements (Figure 2b). Torque results reveal a continuous increase in skin friction with depth, reaching 120 Nm in deeper zones. While this effect can be mitigated by using cones with larger diameters, as employed in the study, it is particularly pronounced in deeper layers of cohesive saturated soils. Skin friction is known to induce overestimation of cone resistance, especially in the deeper layers of plastic soils (EN ISO-22476-2 2005). Following the EN ISO-22476-2 recommendation, a correction for skin friction is applied using torque measurement results.

DF-EFV results show excellent correspondence across the entire profile, while the DF method provides a good match up to a depth of 12 m. These results illustrate the importance of skin friction correction under these test conditions (deeper saturated fine-grained layers).

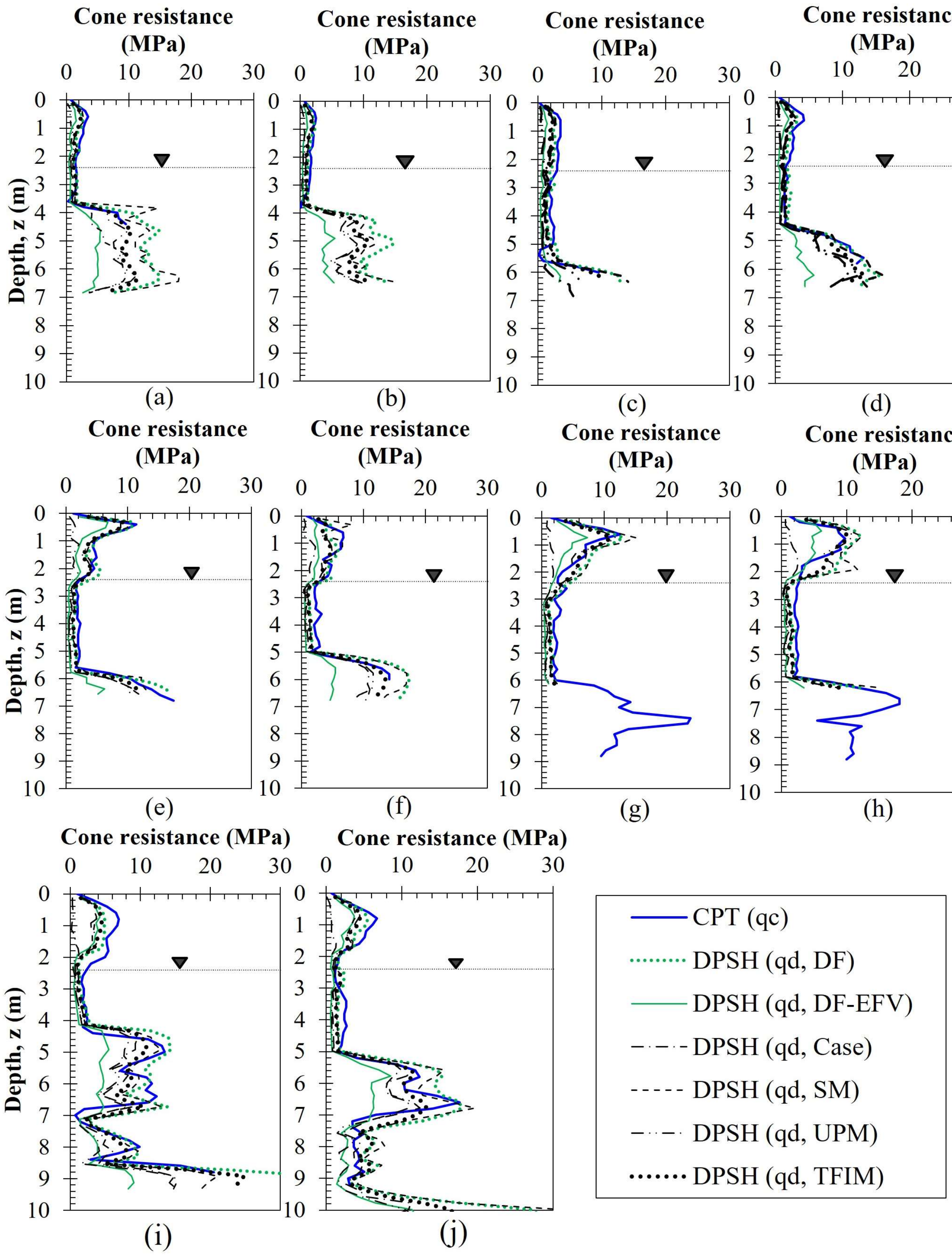


Figure 5. Average resistance profiles for Sète site determined with different methods

The Figure 5 presents the average resistance profiles derived from different methods from DPT data and CPT results for Sète site. Due to the high heterogeneity of this site, the comparisons are conducted for individual measurement points rather than relying on the average profile derived from all site results. A total of ten measurement points were examined, and these are illustrated in Figure 5.

As observed in the Figure 5, like other investigated sites, the Case method consistently produced significantly lower resistance values compared to other methods and to CPT results, particularly for shallow depths (up to approximately 3 m). This trend is particularly evident in Figure 5g, Figure 5h, Figure 5i, and Figure 5j, and it was consistent across most in situ results. Notably, the Case method was initially proposed for driven piles applications, which may explain its tendency to produce inaccurate results for shallower depths, deviating from its typical conditions of application.

In addition, the DF-EFV method also underestimated resistance compared to other methods and CPT results at certain measurement points, specifically in the first layer of Figure 5g and Fig. Figure 5h, as well as the third layer of Figure 5i and Figure 5j. In contrast, overall, the other methods demonstrated good agreement.

Figure 6 summarizes the results by presenting the average ratio between resistance from different DPT methods and CPT for all sites examined.

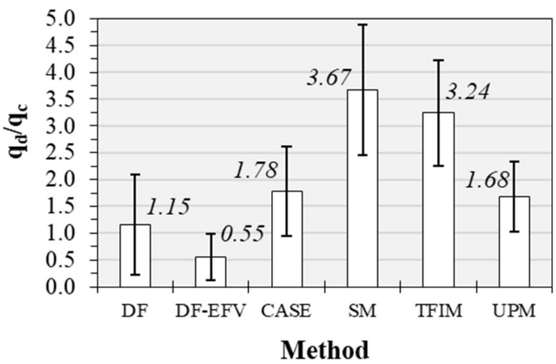


Figure 6. Average resistance profiles for Sete site determined with different methods

Considering overall results presented in Figure 6, DF-EFV was the only method underestimating resistance which produced an overall average ratio of 0.55. Despite often being considered more inaccurate than wave equation-based methods, DF results on average didn't diverge more from CPT results than other methods such as Case and UPM. In contrast, the wave equation-base methods SM and TFIM produced on average considerably higher results q_c. Amongst, wave equation-based methods, UPM exhibited the best overall accordance to q_c even if it also significantly overestimates q_c.

4. Conclusions

This study examines various methods usually employed to derived soil resistance from DPT data. Despite the universal use of DPT for soil characterization and resistance evaluation, a lack of consensus persists regarding the method applied to calculate cone resistance. Taking CPT results as the reference, DPT results produced with different methods are evaluated. The study reveals that, for most methods, there is good agreement with CPT profiles in the shallow unsaturated soils, except for the Case method, which significantly underestimates cone resistance for shallow layers (< 4 m).

The comparison between DPT and CPT results becomes more complex below the groundwater table, particularly for fine-grained soils, due to the different loading rates associated with these techniques. Differences between these techniques can be partially explained by excess pore pressure generated during DPT, especially in saturated fine-grained soils. For saturated fine-grained soils, UPM seemed to produce better results, showing better agreement with CPT. Although further investigations are needed to confirm this hypothesis.

Apart from the interpretation method applied to DPT, other important aspects as correction of skin friction as examined. The importance of applying skin friction correction is demonstrated in order to mitigate cone resistance overestimation especially for higher depths in saturated fine-grained soils. Overall, DF results did not diverge considerable from wave equation-based methods. Its variation, DF with energy measurements, seemed to underestimated cone resistance for most cases, except for saturated fine-grained deeper layers.

Finally, this study shows that by considering some good practice aspects recommended by EN ISO 22476-2 2005 (energy measurement, skin friction measurements and corrections) to DPT, this seems be a simple but cost-effective alternative for cone resistance assessment for shallow unsaturated soils.

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Response to reviewer comments for full paper submitted to 7th International Conference on Geotechnical and Geophysical Site Characterization

Title: Evaluation of Cone Resistance Results from Dutch Formula
ID: 153
SESSION: 35 - Dynamic penetrometers for soil characterization: instruments, models and applications

REVIEWER'S COMMENTS

"An interesting and useful study. To enable the reader to assess the material it would be useful to enlarge the Figures so a true comparison can be made by the reader. Please distinguish between CPT data and CPTM data, Were the CPT data corrected below the water table for u2 pressures? What affect did this have? You comment that above the water table agreement is better, is this pure luck and measurement are small. Are there other corrections to consider below the water table? Do you expect qd to be the same as qc? There are correlations out there, do they work for you? McElmeel NOT McElmee..... Add Site name to title of Figure 4"

AUTHOR'S RESPONSE

The authors gratefully acknowledge the comments on his manuscript entitled "*Evaluation of Cone Resistance Results from Dutch Formula*" submitted to "*7th International Conference on Geotechnical and Geophysical Site Characterization*". The comments and corrections have been a useful source of improvement to the article. Here below the responses to each comment.

- Figures have been enlarged.
- Mechanical CPT have been identified (CPTM) in the data presented.
- Most of CPT didn't include pore pressure measurement. In fact, only two CPTs included pore pressure (the two deeper CPT soundings of Sete site, Figure 5i and j). For CPT including pore pressure measurements, resistance have been corrected. It's important noting that effect of pore pressure at Sete site is not significant as this site is composed of sandy soil or sand, thus ax expected for this type of material $u_2 \approx u_0$ and $q_c \approx q_t$.
- Above the groundwater table agreement is better as it known that water table can significantly impact DPT results. This aspect is mentioned in ISO EN 22476-2 (2005). According to this standard, in fine-grained soils penetration resistance may be increased. Correction of groundwater table effect is proposed by this standard for some specific soil types.
- Even though some corrections exist and can be applied to DPT results below the groundwater table those were not applied in this study. The objective was to present a more direct comparison regarding this aspect. Groundwater table corrections should be considered in further work as results have shown the importance of considering this aspect, notably for plastic soils.
- DPT and CPT differ in many aspects (e.g. geometry, loading rate, vertical resolution). Cone resistance derived from these techniques (q_d and q_c) are not supposed to be the same. However, this study aims to show that by combining best practice rules (e.g. energy efficiency calibration, instrumentation, skin friction correction) and well-adapted analysis/methods to DPT, it is possible to make a more direct comparison of results both techniques. The objective of this study is not to propose a correlation between techniques as number of correlations are already available in the literature for different type of soils.
- The name "McElmeel" on the references have been corrected.
- Site name have been added to legend of Figure 4.